On Tool Wear in Rotary Tool Micro-Ultrasonic Machining

Sandeep Kumar, Akshay Dvivedi and Pradeep Kumar

Abstract Micro-ultrasonic machining (micro-USM) is used to fabricate complex micro-features in brittle and hard materials. In micro-USM, both dimensional and form accuracy of machined component depend mainly on the shape of the tool. However, tool wear is an unavoidable phenomenon of this process, which affect the accuracy of micro-feature. The tool suffers by three types of wear (longitudinal, lateral and edge wear) in micro-USM. Accumulation of micro-chips and abrasives in the machining gap (between tool and workpiece) are the main reasons responsible for severe tool wear in micro-USM. This article reports on a new method named as rotary tool micro-USM to reduce tool wear. The rotary tool micro-USM involves abrasive slurry with providing simultaneous rotation and vibration to the tool. Rotation of the tool helped abrasives to replenish from the machining gap easily. Micro-channels were fabricated and characterized by using stereo microscope. From the results, it was found that rotary tool micro-USM resulted in very less tool wear and as a result of that micro-channels of better dimensional and form accuracy were developed.

Keywords Micro-USM · Tool rotation · Micro-channel · Tool wear · Form accuracy

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Introduction

Ultrasonic machining (USM) is a promising technique used to fabricate complex features in all types of brittle and hard materials viz. quartz, glass, ceramics, silicon, titanium alloys etc. [1]. In USM, material is removed in the form of small chips from workpiece surface by the impact of abrasive particle [2, 3]. Micro-USM is downscaled from macro-USM and it can generate 3D complex micro-feature using simple or complex shaped micro-tools. The final shape of the cavity depends entirely on the shape and size of the tool. The tool wear is an unavoidable phenomenon of micro-USM which affect the accuracy of the micro-feature. Therefore, accuracy of micro-features can be maintained by controlling the shape, size and material of the tool as well. As per literature available, researchers have already demonstrated the feasibility of micro-USM to machine micro-components [4, 5]. Adithan [6] stated that machining rate decreased with decrease in the length as well the weight of the tool. M. Adithan also revealed that poor circulation of abrasive slurry was main the cause of low machining rate and tool wear in USM. Yu et al. [7] reported accumulation of debris in the machining gap results in low machining efficiency as well as high tool wear. Pei et al. [8] reported that the profile of machined surface is greatly influenced by abrasive particles present in the machining gap (between tool and workpiece). Yu and Rajurkar [9] applied a uniform wear method integrated with CAD/CAM software. Uniform wear method resulted in regaining of the shape of the tool while machining of 3D micro-shapes. Cheema et al. [10] reported that tool suffered three types of wear, namely longitudinal wear (face wear), lateral or side wear, and edge wear in micro-USM. Face wear of tool affects the micro-feature depth, whereas side and edge wear results in the taper on micro-feature wall and rounded bottom corners of the feature respectively. To compensate the tool wear in micro-USM. A mathematical model to measure the tool wear in micro-USM without tool rotation was presented by Cheema et al. [11].

In micro-USM tool wear depends on many factors such as frequency of vibration, tool material, workpiece material, amplitude, abrasive material, abrasive size, concentration of abrasive slurry and static load. Some researchers have reported experimental investigations on tool wear by considering above mentioned process parameters. The accumulation of abrasives in the machining gap is one of the main causes of excessive tool wear and poor form accuracy of micro-features in case of micro-USM. Therefore, this study reports on a new method named as rotary tool micro-USM to reduce tool wear. The rotary tool micro-USM involves abrasive slurry and simultaneous rotation and vibration to the tool. Microchannels were fabricated using rotary tool micro-USM. Further the effect of tool rotation speed on tool wear as response characteristics was investigated.

Experimental Setup

Materials and Methods

Microchannels were fabricated on borosilicate glass using a layer-by-layer machining approach [10]. An in-house designed and developed setup of rotary tool micro-USM was used to fabricate microchannels. Schematic representation of experimental setup is illustrated in Fig. 1. The rotary tool micro-USM setup consists of a power supply of 250 W, frequency of 25 ± 1 kHz, range of tool rotation speed from 0 to 2000 rpm and amplitude of 15 μm respectively. Vertical feed was provided to the workpiece with the help of counter weight balance mechanism (Fig. 1). Silicon carbide was used as abrasive material. The tool material selected was tungsten carbide with circular cross section (Ø 600 μm) for the current investigation.

Tool Wear in Micro-USM

Tool wear is an unavoidable phenomenon of micro-USM and it cannot be completely eliminated. However, it can be minimized by controlling input process parameters. In micro-USM, the tool suffers by three types of wear, namely longitudinal wear, lateral wear (face wear) and edge wear. Longitudinal wear is the reduction in the length of the tool which affect the depth of micro-feature, lateral wear is the taper formation around the tool surface which results in taper on side walls of micro-feature. The edge wear is the reduction in the diameter of the tool face and it results in rounded corners at bottom of micro-features [10]. The schematic representation of different types of tool wear is shown in Fig. 2.

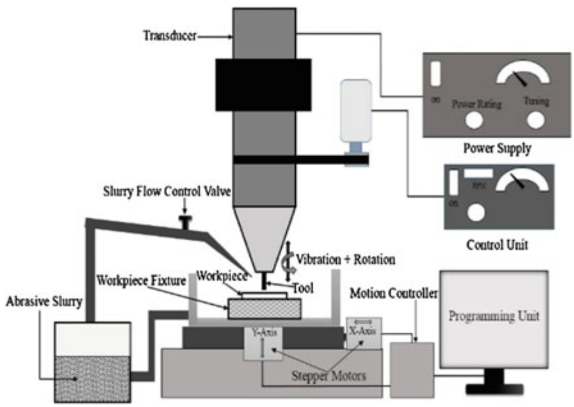

Fig. 1 Schematic representation of rotary tool micro-USM setup [12]

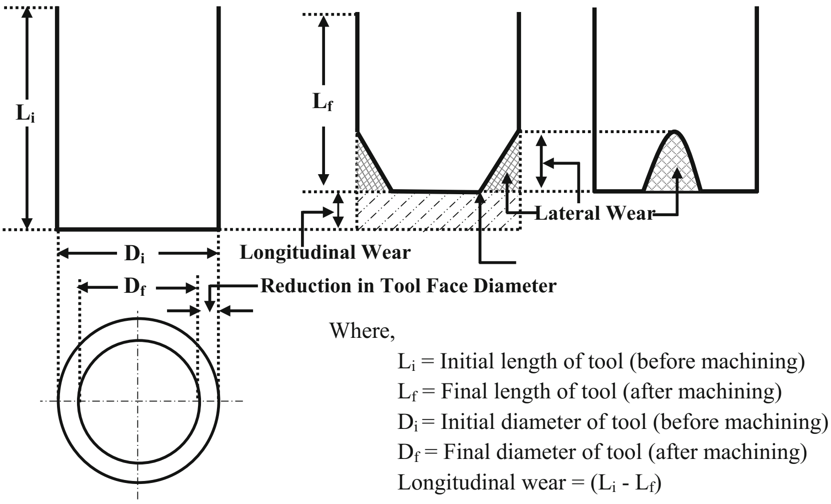

Fig. 2 Schematic representation of tool wear in micro-USM

Process Parameters

The objective of current the investigation was to reveal the effect of tool rotation during micro-USM. Thus, experiments were conducted by varying tool rotation speeds from 100 to 400 rpm. In order to avoid any possible lateral vibrations at higher tool rotation speeds, the tool rotation speed was limited to 400 rpm. The value of other process parameters such as power rating, abrasive size, workpiece feed rate, concentration of slurry and static load were based on published literature [13] and they were kept constant throughout experimentation. Cheema et al. [10] emphasized in there study, that longitudinal tool wear has the largest contribution (86–90) in overall tool wear followed by lateral wear (7–8%) and edge wear (2–3%). Consequently, only longitudinal tool wear was selected as response characteristic in the present study. The values of constant process parameters are given in Table 1. Each experiment was repeated three times and the average value was measured. The length of the tool before and after machining was measured with the help of a stereo zoom microscope (Nikon: SMZ-745T) at a magnification of 50×. Longitudinal tool wear was calculated by subtracting the final length of tool from initial length of the tool. The depth and width of microchannels were measured using image analysis using Dewinter DMI premium optical microscope. The micrograph of cross sectional view of microchannel is shown in Fig. 2.

Table 1 Constant process parameter and their values

S. no.	Process parameters	Values/machine setting
1	Static load (gm)	75
2	Frequency (kHz)	25 ± 1
3	Abrasive size (mesh)	#1000
4	Workpiece feed rate (mm/min)	15
5	Slurry concentration (%)	20
6	Power rating (%)	40
8	Tool diameter (μm)	600
9	Abrasive material	Silicon carbide (SiC)
10	Liquid medium for slurry	Tap water
11	Tool material	Tungsten carbide (WC)
12	Workpiece material	Borosilicate glass

Results and Discussion

The microscopic view of the tool after machining, fabricated microchannel and cross sectional view of microchannels are shown in Fig. 3. In Fig. 3a–d (iii), hatched portion denotes the desired profile of microchannel and double dash chain line denotes the actual profile of microchannels.

Effect of Tool Rotation Speed on Tool Wear, Width and Depth of Microchannel

At tool rotation speed of 100 rpm, it was observed that the tool wear and depth of microchannel were low (as it is shown in Fig. 4) whereas the overcut was large [as shown in Fig. 3a (iii)]. This can be attributed to the fact that at 100 rpm, tool rotation helped the trapped abrasive particles to move away (outward) from the machining gap (between tool and workpiece) but at the same time due to the low rotation speed (100 rpm) of the tool, the circulation of abrasives was not effective. This resulted in a low depth of the microchannel (Fig. 4). Moreover, multiple layers of abrasives kept on flowing in the lateral gap (between tool face and workpiece wall) due to which increased width of microchannels was obtained [Fig. 3a (ii)].

After increasing the tool rotation speed from 100 to 200 rpm, both depth of microchannel and longitudinal tool wear were increased (Fig. 4) whereas the width of the microchannel decreased [Fig. 3b (ii)]. Due to increased rotation speed, circulation of abrasives was improved and more number of abrasives came in contact with the rotating and vibrating tool. This caused an increase in tool wear. Further, the improved circulation of abrasives resulted in a decreased width of the microchannel. Fresh abrasives came into the working gap as the rotation speed was

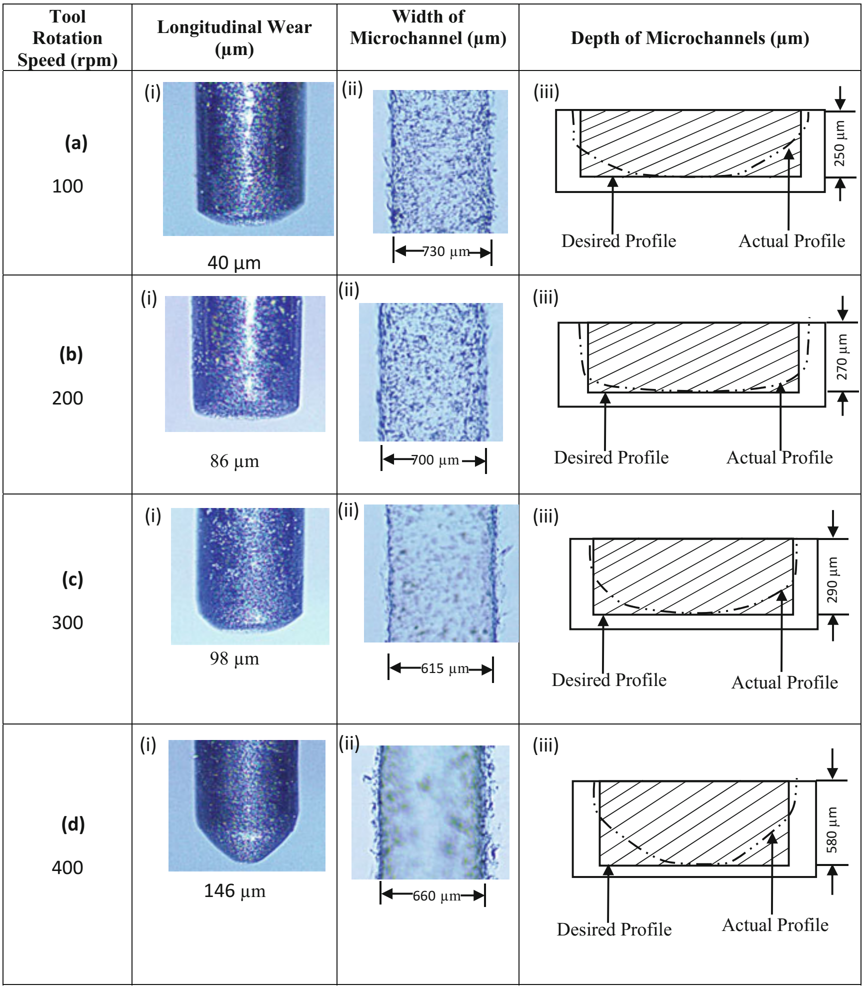

Fig. 3 Microscopic images (45×) of tool [**a**–**d** (i)], microchannel [**a**–**d** (ii)] and cross sectional view of microchannel [**a**–**d** (iii)]

increased. These abrasives further impacted on workpiece surface resulting in more removal of material. Thus, the depth of microchannel was increased.

With further increase in tool rotation speed from 200 to 300 rpm, longitudinal wear and depth of microchannel were slightly increased (Fig. 4) whereas the width of microchannel was decreased [Fig. 3 c (iii)]. This can be explained with the fact that interaction between rotating tool and fresh abrasives was more due to increase in tool rotation speed, which in turn resulted in increasing the tool wear at 300 rpm. Furthermore, a uniform laminar layer of abrasives was observed in between the tool and workpiece. Due to this layer, a good acoustic bond was formed. Subsequently,

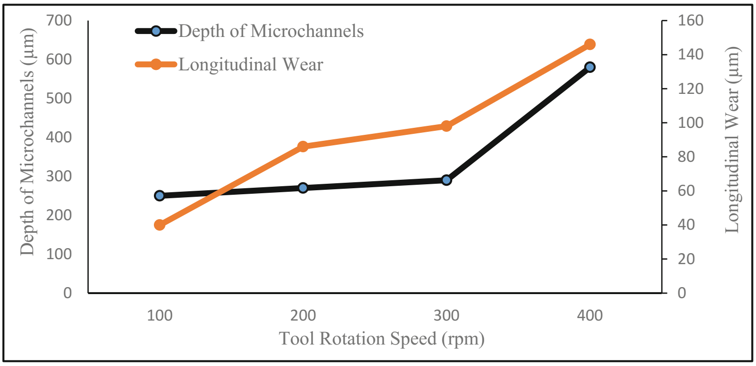

Fig. 4 Effect of tool rotation speed on depth of microchannels and longitudinal wear

the maximum energy was transferred from the abrasive to the workpiece. Thus width of microchannel was decreased and depth of microchannel was increased. This can be evidenced from Figs. 3c (ii) and 4.

On further increase in tool rotation speed from 300 to 400 rpm, tool wear, depth and width of microchannels were increased (Figs. 3d (i), (ii) and 4). It seems that at 400 rpm, the tool exerted high centrifugal force on the abrasives and as a result, less abrasives impacted on workpiece surface. This led to the direct contact of tool and workpiece. Due to the tool and workpiece interaction, lateral wear and edge wear were also dominated at 400 rpm [Fig. 3d (i)]. Therefore, overall tool wear was increased at 400 rpm (Fig. 4). This phenomenon (direct contact between tool and workpiece) was also reported in the literature [10]. Further, the direct contact of tool and workpiece damaged the edges of microchannel as shown in Fig. 3d (ii). The worn tool penetrated inside the workpiece. Consequently, the depth of microchannel was increased and microchannel of deteriorated form accuracy (tapered wall and curved surface) was formed [Fig. 3d (iii)].

Conclusions

The present study focused on the tool wear in rotary tool micro-USM. Microchannels were successfully fabricated at different tool rotation speeds. The following conclusions can be drawn from this study:

- Rotary tool micro-USM possesses the flexibility to fabricate 3D microchannels in all types of brittle and hard materials.
- Tool rotation speed played an important role in deciding the tool wear and form accuracy in rotary tool micro-USM.
- Tool rotation speed of 100 and 400 rpm resulted in large width and poor form accuracy of microchannels.

- The better form accuracy as well as lowest tool wear was obtained at a tool rotation speed of 300 rpm.
- Further, it is necessary to investigate the effect of other process parameters (power rating, abrasive size, workpiece feed rate, concentration) also for desired form accuracy, depth of microchannel and even lower tool wear.

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